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FORMATION OF A COLD AIR LAKE AND ITS EFFECTS ON AGRICULTURE

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ABSTRACT

The general characteristics of cold air drainage and the formation of a cold air lake are described. Intermittent motion of cold air drainage, temperature change due to the flow of cold air and a local circulation model of cold air drainage are discussed on the basis of previous reports in the literature. Observations of conditions on the Sugadaira Highland in Nagano Prefecture, Central Japan, are described. Down slope winds and cold air drainage converged in the basin and flowed onto the top of the cold air lake. A climatological investigation of the relationship between minimum air temperature and the topography of the basin was made and estimated distribution maps were drawn for the Kamikawa and Furano Basins in Hokkaido, which show the dependence of rice yields for 1976, a cool summer.

1. INTRODUCTION

A cold air stream is defined as an airstream which flows down a mountain slope during the night due to the force of gravity. This phenomena has several other names; cold air drainage, cold air flow, and cold air runoff. It also may be called a nocturnal wind, gravity wind or micro-advection.

When the scale of development of the cold air stream increases, it is called (depending on topographical conditions) a down-slope wind, mountain breeze, katabatic wind, or glacier wind. When the scale of the cold air stream is small, it flows down the slope intermittently in a small parcel of cold air. This parcel of cold air is called a cold air drop. If a large temperature difference is recorded between the cold air drop and the surrounding air, it becomes a cold air avalanche. The cold air stream often flows into topographic depressions such as the bottom of a valley or a basin and accumulates there. This accumulation of cold air is called a cold air lake. The diameters of cold air lakes vary from a few meters to several kilometers; large cold air lakes several tens of kilometers in diameter sometimes are formed. Although the terms are not commonly used at present, a large cold air lake has been called a cold air sea, and a small cold air lake a cold air pond. We here report on a cold air stream of relatively small scale, cold air drainage, and discuss results of field observations on the Sugadaira Highland.

Comprehensive reviews of cold air streams have been made by Geiger [5, 6], Vorontsov [16], Baumgartner [1], and Yoshino [18, 20]. Of these, Baumgartner [1] has given details of the motion and accumulation of a cold air stream on slopes and of formation of a cold layer on level plains.

Note: Discussion open until 1 December, 1982.
KEY WORDS: Sugadaira basin, Cold air lake, Cold air drainage, Air temperature inversion, Cool summer damage

In addition, recent studies of these phenomena have been reviewed by Yoshino [21]. Observations on the Sugadaira Highland have been conducted by Nakamura [8, 9, 10] in recent years.

This paper deals with the general characteristics of cold air drainage and formation of a cold air lake, based on observations made on the Sugadaira Highland, Central Japan, in October 1980. Effects on agricultural production of cold air lakes which settle in basins are discussed with examples given for Hokkaido.

2. CHARACTERISTICS OF COLD AIR DRAINAGE

2.1 Intermittent Nature of the Flow

At night, cold air streams intermittently flow down slopes. This intermittent flow is a result of frictional force created by obstacles such as vegetation which prevent the cold air drop from flowing until the force of gravity overcomes it. In valleys or on slopes of sufficient size, large scale cold air drainage may develop 3 to 4 times during a night. Normally, this is called an outflow of cold air. Although it depends on weather conditions and the area of the drainage basin of the cold air, this outflow often takes place 1 or 2 times between sunset and midnight and 2 or 3 times between midnight and sunrise. The final outflow of this cold air produces the minimun temperature of early morning.

2.2 Cold Air Drainage and Temperature

Because cold air drainage is the motion of the cold air drop, the temperature of the surface boundary layer at a fixed height drops when this drainage moves into a given area. Since the thickness of cold air drainage depends on topographical and weather conditions, and on the season of the year, it is difficult to generalize the height (thickness) of the cold air in the surface boundary layer, the place where the drop in temperature is best observed. Observations made near the center of the cold air drainage show that this temperature drop is striking. After passage of the cold air, the air temperature rises due to the inflow of warm air from aloft or from the surrounding area. Observations of several cold air drops show that periodic changes in temperature take place.

Experimental and theoretical equations for cold air drainage have been discussed by Reiher [13], Fleagle [3] and Sahashi [14], as well as in the reviews cited above.

It now is necessary to distinguish between the formation, source regions, and outflows of cold air drainage in order to form more definitive descriptions of this phenomenon.

2.3 Circulation of Cold Air Drainage

Cold air drainage flows down to valley bottoms along the relatively lower parts of slopes due to the force of gravity. The cold air which accumulates in the valleys flows further down to the lower courses of rivers as a mountain breeze. But, when the valley is curved, it may slightly climb the slope which faces the river from upstream. It also may slightly climb the opposite slope when two valleys merge.

2.4 Model of Cold Air Drainage

On the bases of various observations and records several models of cold air drainage have been formed. These models have the following common characteristics.

When cold air flows down a slope, a compensating current is present above the cold air drainage. Part of the cold air drainage flowing down the slope will be absorbed into the cold air lake, and the rest of this drainage will enter the layer above the cold air lake. Estimates of the vertical profile of the air temperature at the lower end of the slope and in the valleys or basin bottoms show that the cold air lake is an inversion layer of air temperature in which the wind speed is low, less than 1 m/sec in most cases. Above this thin layer of cold air drainage, the compensating return flow has a relatively uniform air temperature, and the lapse rate, if any, is small. The vertical thickness of the cold air lake at the bottom of a valley or basin is about 1/4–1/5 the altitude between the bottom and surrounding mountains. Above the circulation system of cold air drainage, (above the return flow), there is a synoptic scale wind. When the synoptic scale wind overflows the mountains from the other side and enters the valley or basin, another inversion layer is formed between the warm layer of air produced by the subsidence of this airflow and the original air layer in the valley or basin.

3. COLD AIR DRAINAGE AND COLD AIR LAKES ON THE SUGADAIRA HIGHLAND

3.1 Observations

There were two objectives in our reseach on the Sugadaira Highland. Simultaneous wind observations on two opposing slopes facing the cold air lake were made in order to clarify the relationship between the outflow of cold air and formation of a cold air lake. And, air temperatures were recorded in several cold air lakes, which formed in the same valley.

The Sugadaira Highland geomorphologically is composed of two parts; the Sugadaira Basin (1,250–1,600 m a.s.l.) and the volcanic slope (1,300–1,800 m a.s.l.) of Mt. Neko. One main valley opens southward to Sanada and the other northward to Nire and Senni (Fig. 1). Observations were conducted from the evening of October 22 to the morning of October 25, 1980. During this period, thermographs were placed at 13 points within the Sugadaira Basin, at 4 points in the valley

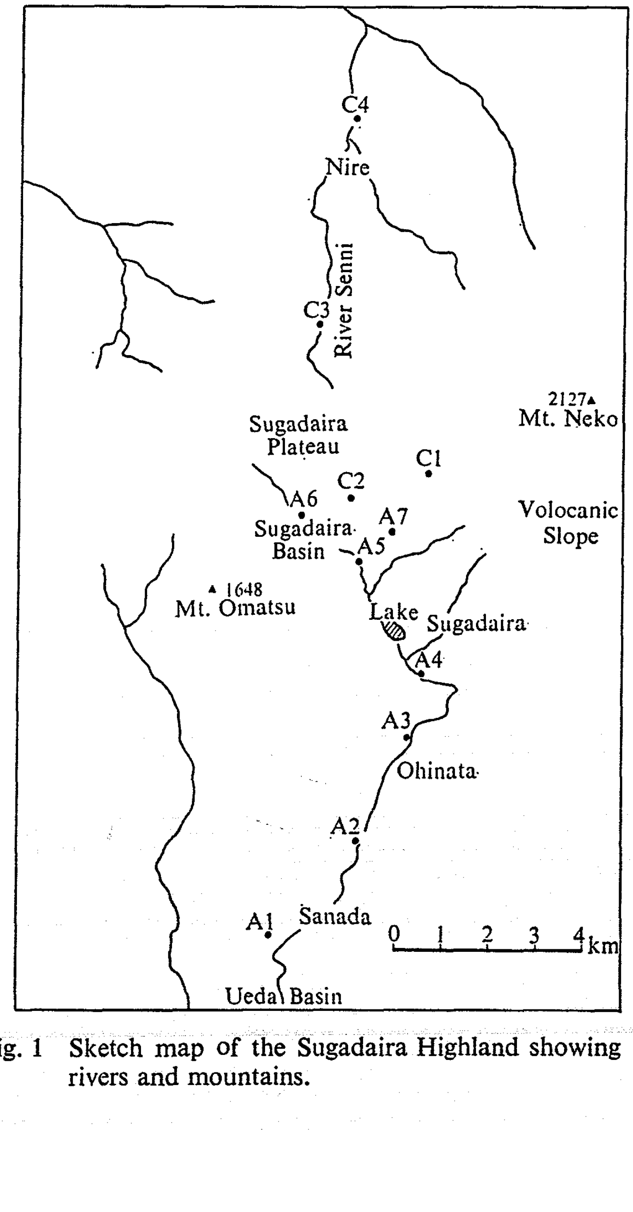
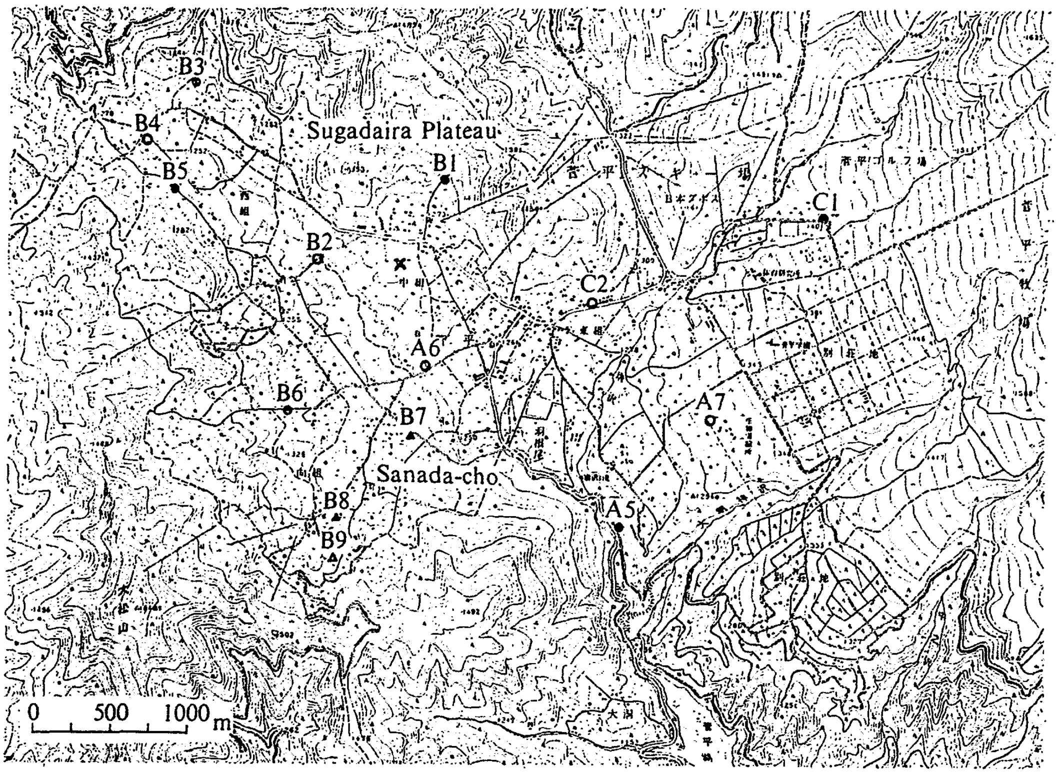


Fig. 1 Sketch map of the Sugadaira Highland showing its rivers and mountains.



• Thermograph
▲ Self-recording anemometer and wind vane
o Thermograph and anemometer
▲ Thermograph and self-recording anemometer and wind vane
× AMEDAS station

Fig. 2 Locations of fixed observation points on the Sugadaira Highland.

toward Sanada, and at 2 points in the valley toward Nire and Senni. Mobile observation with thermister thermometers mounted on vehicles were made in the early mornings (05:00–05:40) of October 23 and 24. Three vehicles were used to cover the entire Sugadaira Basin area and the valleys toward Sanada and Nire. Similar mobile observations were conducted during the afternoons of October 23 (13:00–14:40) and October 24 (13:00–13:30) to obtain the distribution of air temperatures during daylight.

In addition to these temperature recordings, Makino wind vane and anemometers (which automatically record wind direction and speed) were placed at three points on the northeast-facing slope of Mt. Omatsu. During mobile observations in the early mornings and afternoons, wind direction and speed were recorded at five fixed observation points within the Sugadaira Basin with Nakaasa-type portable wind vanes and anemometers. The distribution of these fixed observation points is shown in Fig. 2.

Hourly air temperatures, the duration of sunshine and 3 hourly wind records taken with AMeDAS at Sugadaira and Ueda are shown in Fig. 3. The synoptic conditions during the observation period were as follows: On October 22, the winter monsoon pattern prevailed. A northerly wind of 2–3 m/sec and snow was observed on the tops of Mt. Neko and Mt. Azumaya. During the daytime, there was considerable cloudiness which dissipated by evening. On October 23, a migratory anticyclone passed over the southern part of the Sea of Japan and a light wind and clear sky were recorded. On October 24, a thin layer of cirrostratus clouds covered the sky from 06:00 and, by afternoon, insolation had been cut off by dense clouds. From the evening of October 24 to 25, twin cyclones passed over the Sea of Japan and off the southern coast of its main island, Honshu. Light rain and a strong southerly wind were recorded. The temperature differences between Ueda and Sugadaira was large from October 22 to 24 when the weather was clear and cold

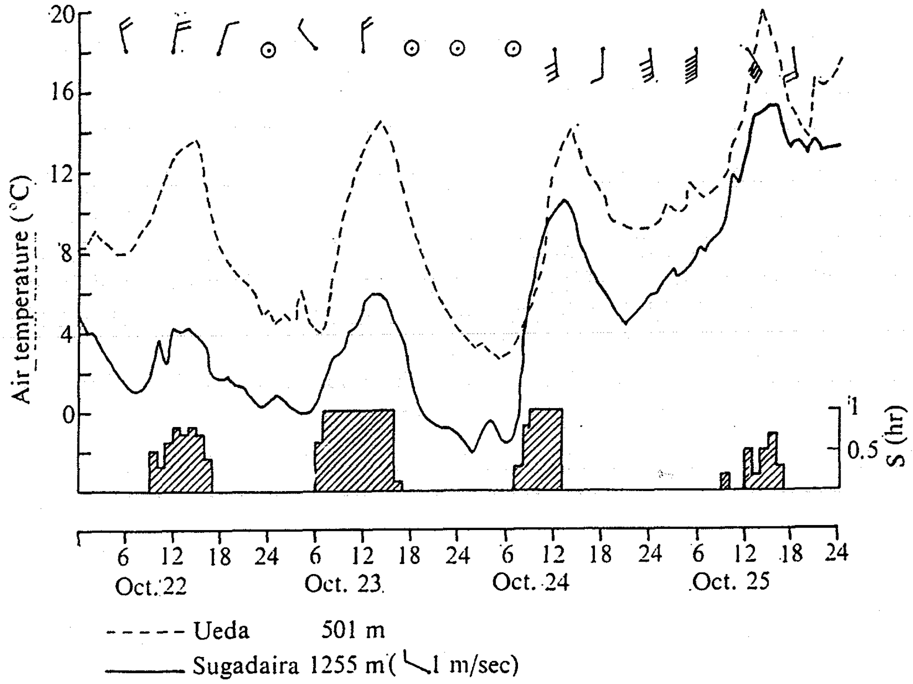


Fig. 3 Time changes in temperature, on the Sugadaira Highland and at Ueda, with duration of sunshine and wind on the Sugadaira Highland from October 22 to 25, 1980. Recorded by AMeDAS.

air was present at the higher level. After this period, warm air invaded the area and the lapse rate decreased.

Temperature conditions at two locations within the Sugadaira Basin are shown in Fig. 4. One location (C1) is on the southwest-facing slope of Mt. Neko above the cold air lake. The second location (B2) is at the bottom of the basin in the center of the cold air lake. In the early morning of October 23, there was a small cold air lake; but the air temperature decreased with height in most parts of the Sugadaira Basin. This cold air lake rapidly developed after 18:00 on October 23, and reached its peak intensity between 03:00 and 06:00 on October 24, when there was an air temperature inversion of 5 °C within the Sugadaira Basin. After this period, the weather became unfavorable (strong wind and light rain), and little difference in temperature was found

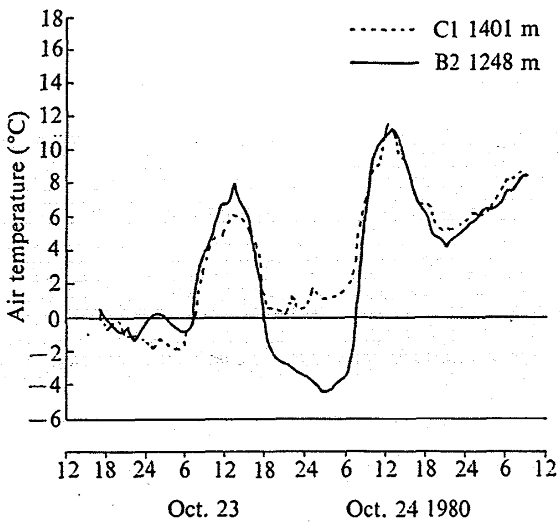


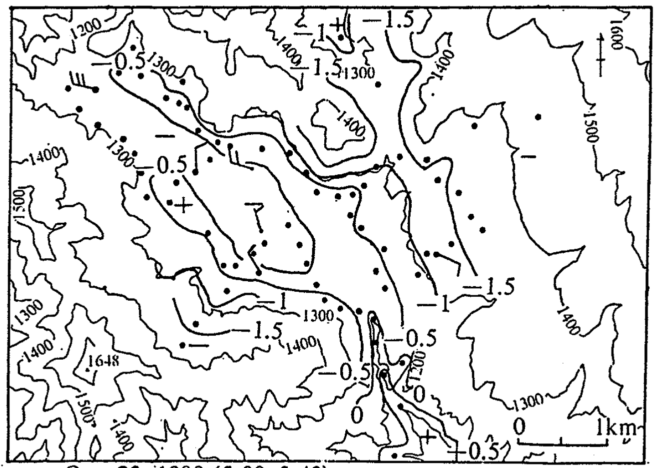
Fig. 4 Time changes in temperature at the bottom of the Sugadaira Basin (Point B2, 1248 m) and on a slope (Point C1, 1401 m).

within the basin. During the early mornings of October 23 and 24, several cold air lakes formed in the valleys of Sanada and Senni.

3.2 Formation of the Cold Air Lake in the Sugadaira Basin

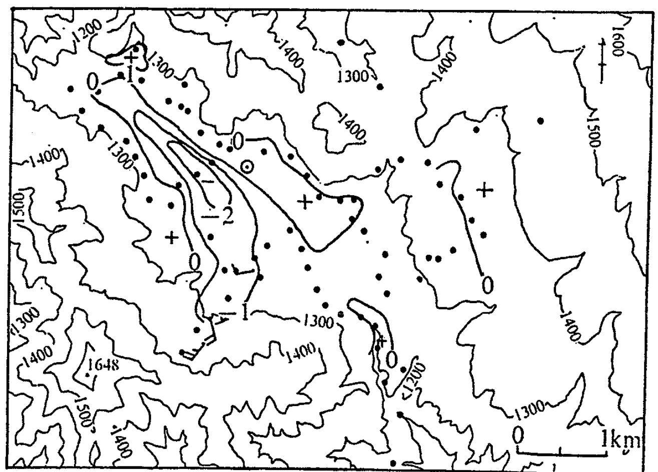
The air temperature and wind for the early morning of October 23 are given in Fig. 5. There was northerly wind of 1 m/sec at Nakagumi in the Sugadaira Basin, which indicates the advection of cold air from the north. As a result, at an elavation of 1,156 m a.s.l. (north of Lake Sugadaira), the air temperature was 1.5 °C higher than that recorded on the northern slope facing Senni (1,150 m a.s.l.). Because of this northerly wind, only a small scale cold air lake developed in the basin. This lake had a thickness (depth) of 18 m and an inversion of 0.3 °C. Temperature decreased with height above this layer; there was a 1.7 °C difference between 1,266 m and 1,400 m a.s.l. (Point C1) on the southwest-facing slope of Mt. Neko.

During the daylight hours of October 23, the northerly wind continued, and air temperature decreased with height in the Sugadaira Basin. As the travelling anticyclone moved eastward the northerly wind quickly abated. By 19:00 (Fig. 6) a cold air lake with a temperature of −2 °C had developed in the bottom of the basin. On the northeast-facing slope of Mt. Omatsu, cold air drainage of 1–1.5 m/sec was recorded.



Oct. 23, 1980 (5:00–5:43)

Fig. 5 Temperature and wind on the Sugadaira Highland in the early morning hours from 05:00–05:43, October 23, 1980.



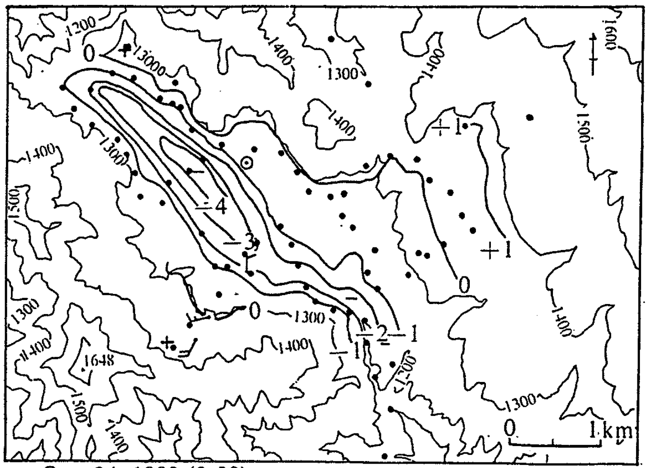
Oct. 23, 1980 (19:00)

Fig. 6 Temperature and wind on the Sugadaira Highland at 19:00, October 23, 1980.

The cold air lake gradually intensified during the night. At 03:00 on October 24, it reached peak intensity (Fig. 7). The air temperature showed a marked inversion throughout the Sugadaira Basin.

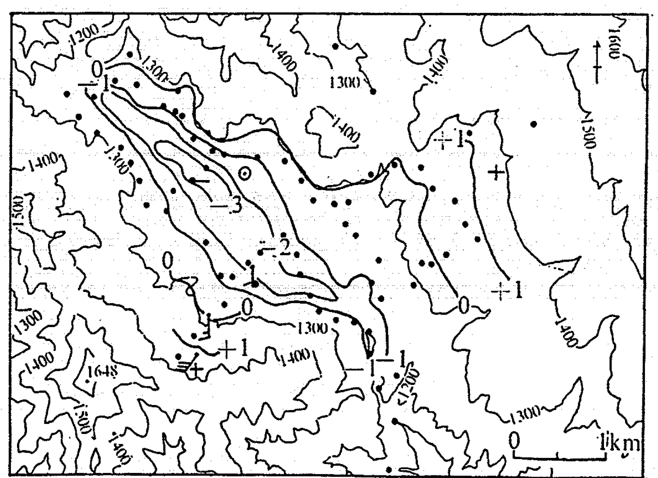
There was an inversion of 5.0°C between Point C1 (1,401 m a.s.l.) and Point B2 (1,248 m a.s.l.). Detailed inspection shows that below the elavation of 1,266 m a.s.l. existed a very strong inversion which was about 18 m thick and showed a 3.6°C inversion (coinciding approximately with the area below −1.0°C). Above this layer, there was a weak, but very thick inversion layer of at least 140 m, indicated by the difference in temperature between the bottom of the basin and the lower part of the northeast-facing slope. The inversion layer strongly influenced wind conditions during the dissipating stage of the cold air lake.

Conditons from 05:00–05:40, when mobile recordings also were made, are shown in Fig. 8. Because of the thin cirrostratus clouds, the air temperature rose about 1°C. On the northeast-facing slope of Mt. Omatsu, cold air drainage of 1–2 m/sec was recorded from the southwest, the direction of the higher part of the slope. On the southwest-facing slope of Mt. Neko, cold air drainage of 1.5 m/sec from the northeast was recorded. These data are evidence that winds converge above cold air lakes. Within the cold air lake, there was virtually no wind, as shown by the circle in Fig. 8. The thermograph located near the fringe of the cold air lake showed oscillating



Oct. 24, 1980 (3:00)

Fig. 7 Temperature and wind on the Sugadaira Highland at 03:00, October 24, 1980.



Oct. 24, 1980 (6:00)

Fig. 8 Temperature and wind on the Sugadaira Highland at 06:00, October 24, 1980.

temperatures during the night. A weak heat island was recorded in the small settlement of Higashi-gumi. After sunrise, the cold air lake dissipated quickly.

3.3 Diurnal Changes in Air Temperature and Winds on the Sugadaira Highland

As shown on the map of horizontal distribution, by 18:00 of October 23, cold air drainage down the northeast-facing slope of Mt. Omatsu toward Point B2 at the bottom of the basin had been established. The time changes in temperatures and winds recorded on the northeast-facing slope of Mt. Omatsu with the thermograph and the Makino wind vane and anemometers are shown in Fig. 9. The direction and speed of the wind was read every 15 minutes. At Point B9, on the upper part of the slope, a wind of about 2 m/sec was recorded. At Point B8 in the middle of the slope, the wind was about 1 m/sec, but at Point B7 near the bottom of the basin, its speed was less than 0.5 m/sec. Hence, wind conditions in the cold air lake were nearly calm. After 07:00 on October 24, a strong southerly wind began to blow which persisted until the end of our observation period. This wind was recorded first at Point B9. Nocturnal cold air drainage blew until 06:50 at Point B9, 06:35 at Point B8 and, although weak, blew until 07:15 at Point B7. At Point B8 in the middle of the slope, the air temperature tended to rise during the night as cold air drainage weakened, but, at Point B7 located within the cold air lake, the air temperature rose as the wind speed increased. This is the same general tendency found for the relationship between air temperature and wind speed in the air layer near the ground during the night. Hence, the relationships

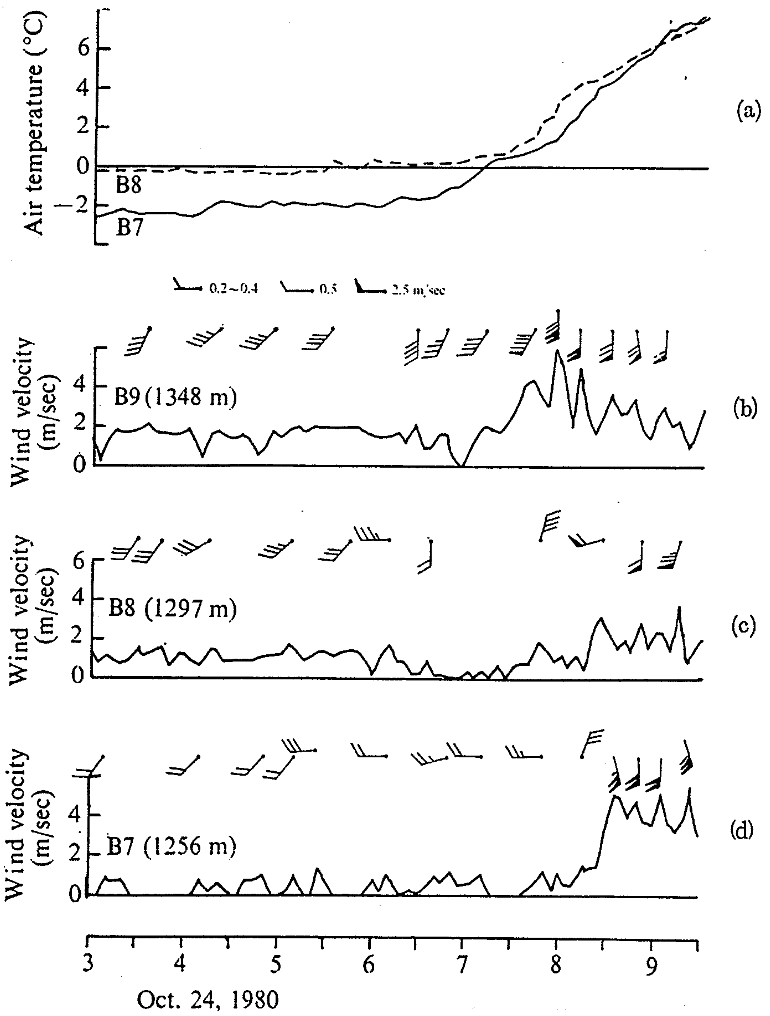


Fig. 9 Time changes in wind velocity and air temperature in the cold air lake and on an adjacent slope in the Sugadaira Basin from 03:00 to 09:00, October 24, 1980.

between wind speed and air temperature were opposite for Points B8 and B7.

The temperature inversion between Point B7 and Point B8 weakened rapidly after 06:30, and the cold air lake had dissipated by 07:10. Winds had temporarily stopped at all points on the slopes around this time. This calm was recorded at Point B9 at 06:55, at Point B8 about 07:00 and at Point B7 about 07:30. After this brief calm, the middle of the slope became heated due to insolation and the air temperature rose at Point B8. A valley breeze was recorded at Point B8 after about 07:45. Strong wind from aloft descended toward the bottom of the valley as the inversion layer over the entire Sugadaira Highland weakened. This wind reached Point B7 by 08:30.

3.4 Formation of Cold Air Lakes in the Valleys of Sanada and Senni

During the morning of October 23, only a small cold air lake developed in the Sugadaira Basin because of advection from the north (from the Senni valley). But, toward Sanada on the leeward side of the valley two cold air lakes developed. One cold air lake developed at an elevation of 1,100 m a.s.l. above the bottom of a valley 300 m deep. This lake had a depth of 50 m and showed a strong inversion of 2.3 °C. A second cold air lake developed at an elevation of 900 m a.s.l. above the bottom of a valley about 650 m deep. This cold air lake had a depth of 110 m and an inversion of 0.5 °C. On the windward side of the valley toward Senni, a weak cold air lake developed at an elevation of 900 m. This lake had a depth of 110 m and an inversion of 0.5 °C.

Diurnal variations in air temperature for the morning of October 23, recorded by thermographs in the valley of Sanada, are shown in Fig. 10. A cold air lake developed near Point A4. Hence,

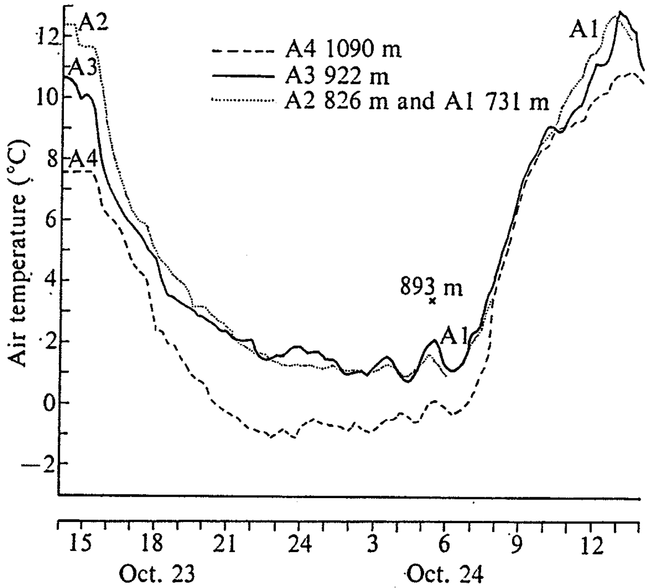


Fig. 10 Time changes in temperature at 3 points in the Sanada valley from 18:00, October 22, to 14:00, October 23, 1980.

values for temperatures, read every 15 minutes from three thermographs in the valley, are shown. During the evening of October 22, the wind from the north was strong and air temperature decreased with height. As the wind slowly weakened during the night, a strong inversion rapidly developed near Point A4 after 03:00 on October 24. At 06:30, the insolation reached the bottom of the valley and the cold air lake dissipated rapidly. The air temperatures at the top of this cold air lake, recorded with mobile observation, are shown in this figure by the symbol(x).

On the morning of October 24, the cold air spread out from the cold air lake in the Sugadaira Basin and down to Lake Sugadaira. In the valley of Sanada, the top of an extremely large cold air lake extending from Ueda (elevation 500 m a.s.l.) reached about 890 m a.s.l. It had a 1.5 °C inversion. The top of the inversion layer on this morning was about 130 m higher than the climatological thermal belt of the Ueda Basin reported near the village of Osa (765 m a.s.l.) in a study by Yoshino [19]. In the valley toward Senni, the larger cold air lake had an inversion top at an elevation of 1,080 m a.s.l.

3.4 Conclusions about Field Observations on the Sugadaira Highland

Our observations of the formation and dissipation of cold air lakes on the Sugadaira Highland showed that when the cold air lake in the basin of the highland reached its peak intensity during the early morning of October 24, the down-slope winds on both of the side slopes of the basin converged over the cold air lake. These cold air drainages were clearly recorded as a southwesterly wind of 1–2 m/sec on the northeast-facing slope of Mt. Omatsu, and as a northeasterly wind of 0.5 m/sec on the southwest-facing slope of Mt. Neko. Cold air drainage on the slope of Mt. Omatsu reached aproximately 2 m/sec over the lower parts of the slope, but it was nearly calm in the cold air lake at the bottom of the basin. Hence, the cold air drainage mostly flowed onto the top of the cold air lake. Cold air lakes also were recorded in the valleys of Sanada and Senni. Even during the early morning of October 23, when development of the cold air lake on the highland was poor, a strong cold air lake had been formed at Sanada.

4. COLD AIR LAKES AND AGRICULTURAL PRODUCTION

4.1 Temperature Inversion in the Basins of Hokkaido

The Kamikawa Basin is located in central Hokkaido. It has a south-north axis of about 200 km and an east-west one of 60–80 km. Below a height of 400 m a.s.l., the relationship between the monthly mean daily minimum temperature in January, t, from 1941 to 1970 and the height above sea level, h, shows that inversions took place at a rate of 0.84°C/100 m. Its regression line is expressed by the following exprimental equation:

$$t = 0.0084h - 16.83 \qquad (r = 0.55) \qquad (1)$$

Above a height of 500 m a.s.l., this relation is given by a different equation, because it is a lapse condition.

The mean monthly minimum temperature for 1966–1975 in the Kamikawa Basin also shows an inversion condition, which may be caused by a strong inversion layer of cold air lakes. The upper limit for strong inversion changes from winter to summer is shown in Fig. 11; it is more than

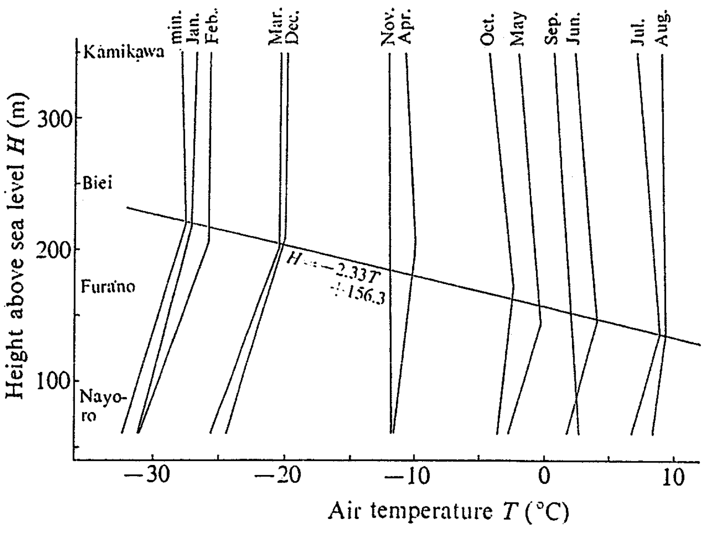


Fig. 11 Monthly mean daily minimum air temperature and height above sea level in the Kamikawa region of Central Hokkaido from January to December and minimums recorded for 1966–1975.

200 m a.s.l. during the winter months and lower than 150 m during the summer. As shown in Fig. 11, the height H of the upper limit of the inversion is related to air temperature T by the following regression line:

$$H = -2.33T + 156.3 \qquad (r = -0.97) \tag{2}$$

It is important to note that a well developed cold air lake is shallow in the warmer months which has an effect on agricultural harvests.

4.2 Rice Yields and Cold Air Lakes

In Hokkaido, cool summer damage to rice crops took place in 1971, 1976 and 1980. We have estimated the monthly mean air temperature distribution during August, 1976, making use of the relation of mean temperature to height. By placing the recorded values for August, 1976, in the climatological relationship between the monthly mean air temperature in August and height, we could plot isotherms on a topographical map (original scale, 1:200,000). This map is shown in Fig. 12.

The rate R of cool summer damage to rice is defined as

$$R = \frac{\text{(Normal yield)} - \text{(Yield in 1976)}}{\text{(Normal yield)}} \times 100\ (\%) \tag{3}$$

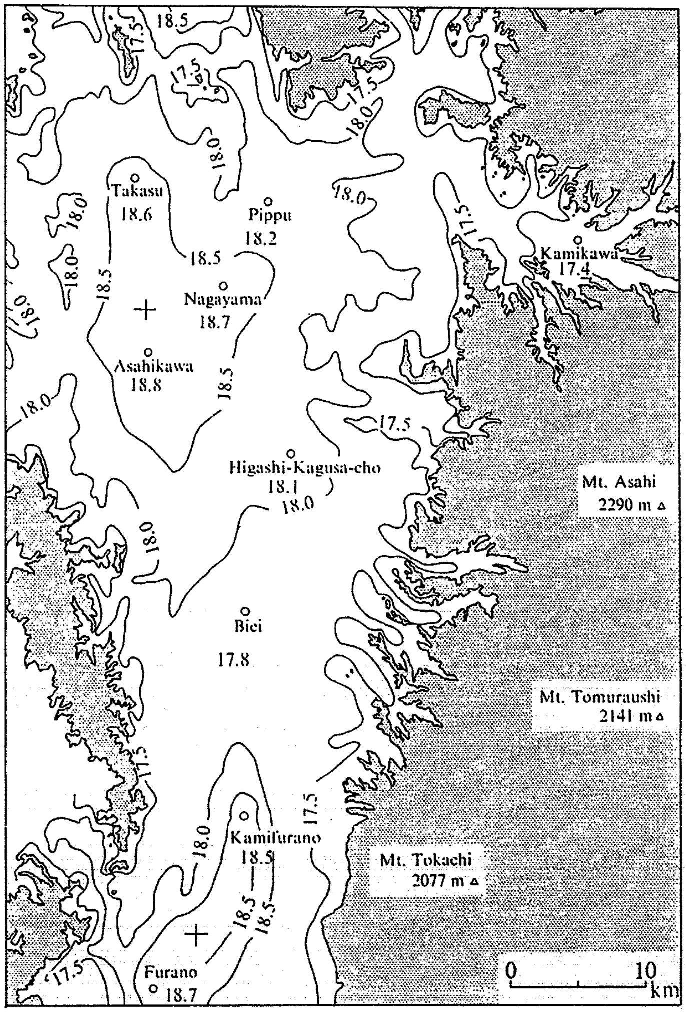


Fig. 12 Monthly mean air temperature in the Kamikawa region in August, 1978, below 500 m a.s.l.

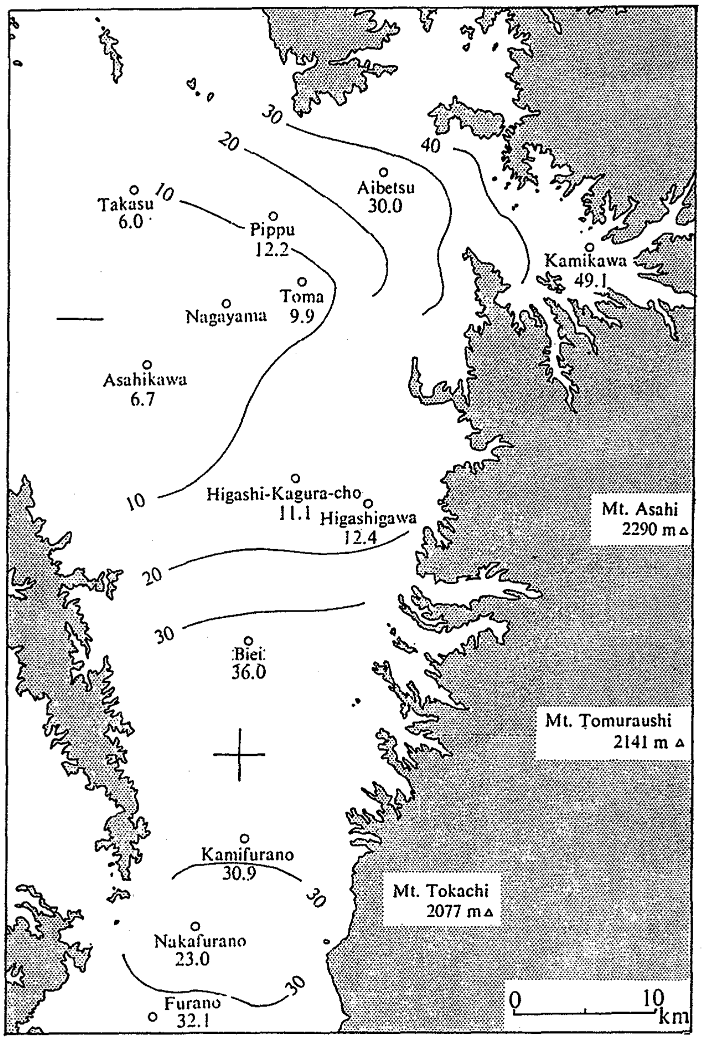


Fig. 13 Distribution of cool summer damage to rice in the Kamikawa region in 1976.

where normal yield means long-year-mean for yields. The yield for 1976 was measured on October 15, 1976. The distribution of the rate of cool summer damage to rice in 1976 is shown in Fig. 13.

A comparison of Fig. 13 with Fig. 12, shows the following facts: (1) The higher air temperature area (above 18 °C) surrounding Asahikawa coincides with the area with the lower *R* value. (2) The higher the air temperature, the lower the *R* values in the Furano area. The absolute value of *R*, however, is much larger for the Furano area than for the Asahikawa area. (3) The Biei area has air temperatures lower than 18 °C, as its *R* value is higher than 36. This is a much better condition than that found for the Kamikawa area. (4) The reason, why the Furano area and the Kamikawa area have relatively high *R* values, is attributable partly to the cold air lakes formed in these basins and partly to the lower temperatures of the waters that irrigate these basins located near high mountain areas.

Studies of the damage to rice in the Hokkaido and Tohoku Districts during the cool summer of 1980 showed that the effects of agrometeorological elements on rice cultivation are complicated and differ from region to region [4]. For example, Yoshida et al. [17] pointed out that the accumulated temperatures for July and August showed a high correlation with the ripening of rice in Hokkaido during the cool summer of 1980. Therefore, in addition to analyses of macro- and mesoscale conditions, the effects of micro-scale conditions, such as cold air lakes, should be analyzed in detail.

5. DISCUSSION

The data recorded for the Sugadaira Highland in October, 1980, confirmed that down-slope cold air (cold air drainage) flows on the lower parts of mountain slopes on clear night. Part of this air flows down onto the top of the cold air lake formed in basin and the rest merges with the cold air lake. The depth of a cold air lake which has a sharp inversion of air temperature is 1/4–1/5 the difference in height between the bottom of the basin and the surrounding mountain ridges. This cold air lake is thicker in winter than in summer.

Cold air drainage generally occurs in cycles. According to a theoretical study by Fleagle [3], as the air accelerates down the slope, adiabatic heating results in a reverse pressure gradient which retards the flow. As the air decelerates, friction decreases, radiation cooling increases the pressure gradient and the cycle is repeated. But, in nature, adiabatic heating effects are negligible because the difference in height for the cold air flow is small.

Data from recent years indicate that relatively large-scale down slope winds (mountain breezes) have a period of oscillation of 1 to 3 hours (Tyson [15], Petkovšek and Hočevar [12], Manins and Sawford [7]). Doran and Horst [2] showed that peaks in the spectra of the time series of wind speeds and temperatures for cold air drainage from a large drainage region are formed at frequencies corresponding to periods of oscillation of $\sim$1.5 h.

Nakamura [11] formulated experimental equations for measuring the speed (U) of cold air drainage in relation to the distance covered (L) on a gentle (4°) slope. $U=1.48L^{1.57}$ on a snow field and $U=1.30L^{1.49}$ on a cultivated field. This means that a flow covering a distance of about 600 m on a snow field is needed to attain a speed of 1.0 m/sec, and one covering 700 m is needed on a cultivated field. Based on these data, the conditions of microtopography and cold air drainage have been summarized as shown in Table 1.

The output of much agricultural production is affected by whether cold air lakes are formed; for example, cool summer damage to rice is striking wherever cold air lakes develop.

Table 1 Microtopography and cold air drainage

Microtopography	Source, runoff or stagnant region	Characteristics of cold air drainage
Upper part of slope	Source region	Positive correlation between the wind speed of cold air drainage and air temperature. Ground surface temperature is colder than air temperature.
Middle part of slope	Runoff (drainage) region	Cold air drainage is well defined in the time series of changes in air temperature, wind speed and wind direction. After cold air passes, the air temperature rises.
Lower part of slope	Runoff (drainage) region	Cold air drainage is well defined in the horizontal distribution of air temperature, wind speed and wind direction. Above the down-slope cold air drainage, there is an antidown-slope wind. Advected air is warmer than the original air cooled by radiation. There is a negative correlation between wind speed and air temperature.
Valley bottom or basin bottom	Stagnant region (cold air lake)	Well defined by a strong inversion in air temperature. Little defined by extent of area. Advected air is, in most cases, cooler than the original air cooled mainly by radiation.

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